



Silk damping in induced GWs: a novel probe of new physics

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YHY, S. Wang, SCPMA 68 (2025) 210412

YHY, Z. Chang, S. Wang, JCAP 02 (2026) 011

Outline

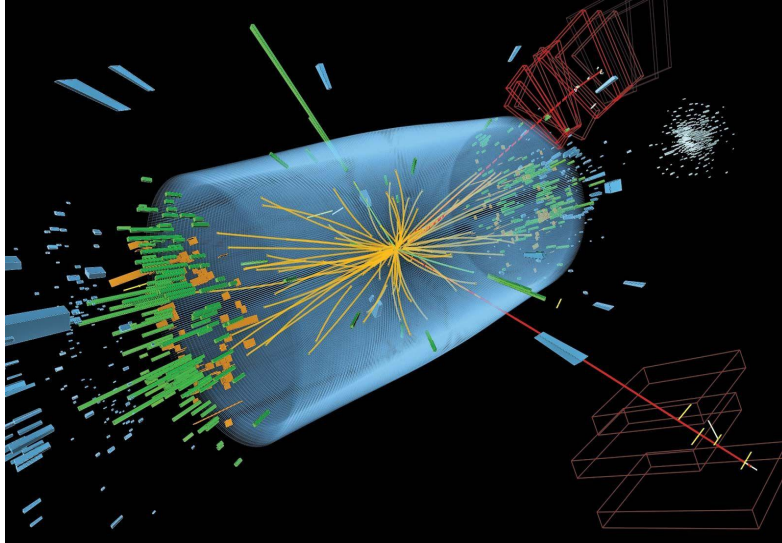
- 1. GWs & HEP**
- 2. Silk damping in induced GWs**
- 3. Probing weakly-interacting particles**
- 4. Summary**

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- 1. GWs & HEP**
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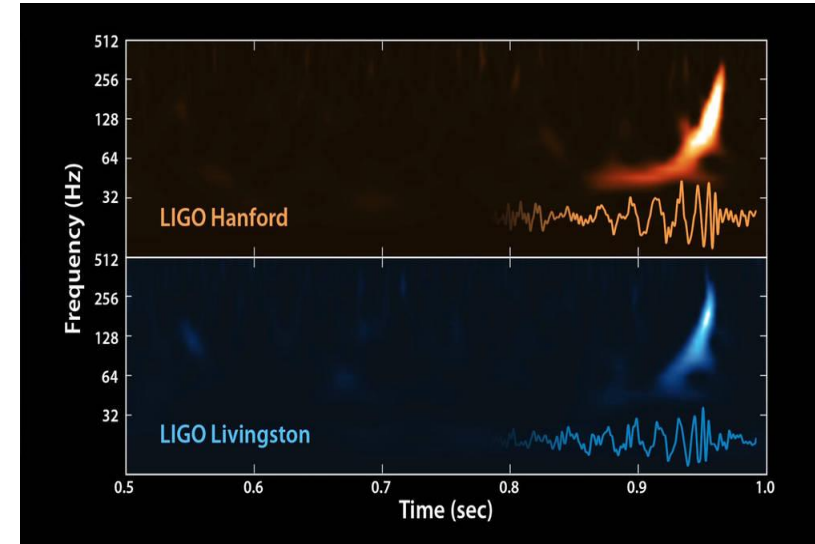
GWs & HEP

Higgs bosons (2012)



BSM physics?

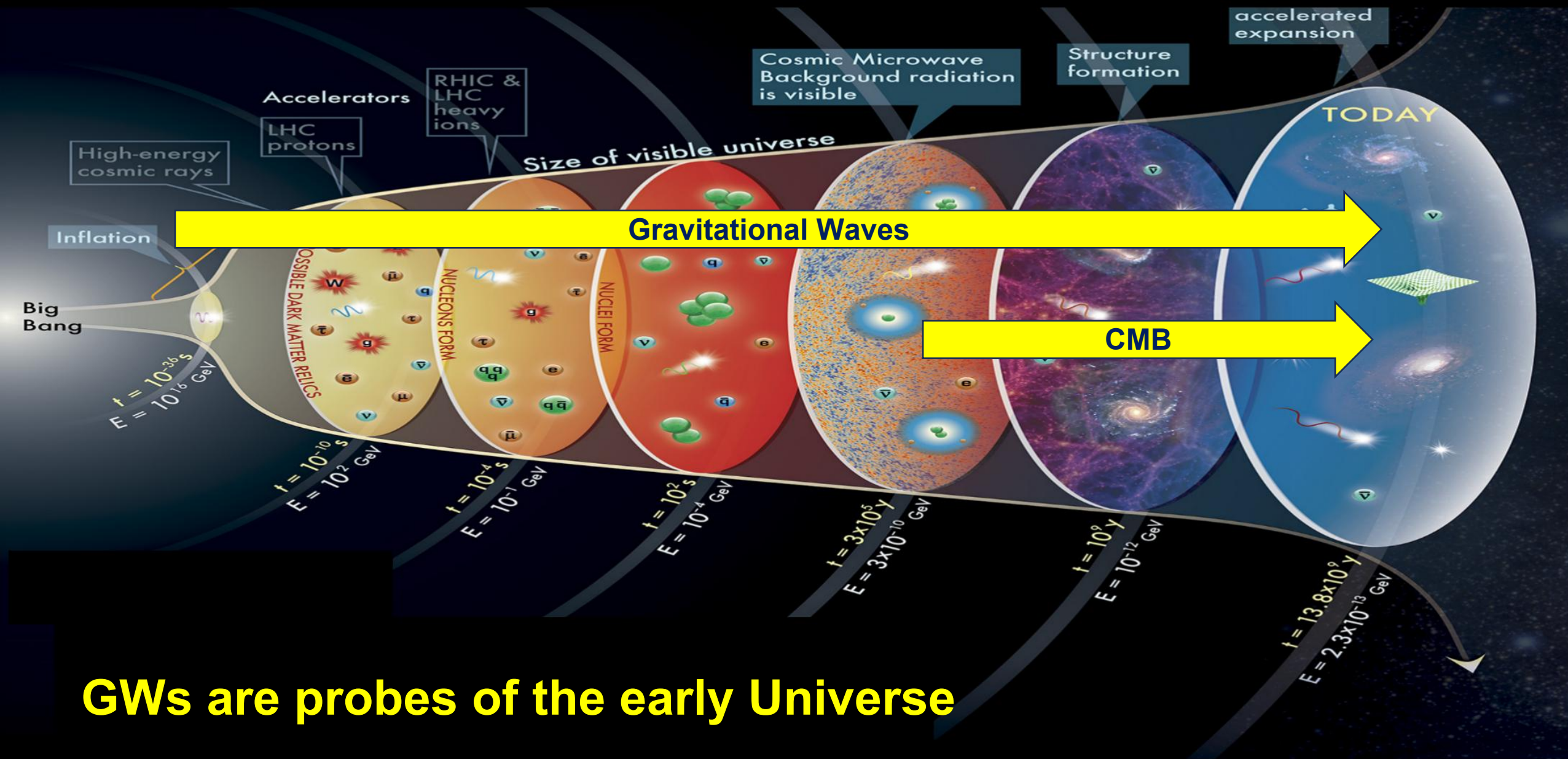
Gravitational waves (2016)



GW astronomy
& cosmology

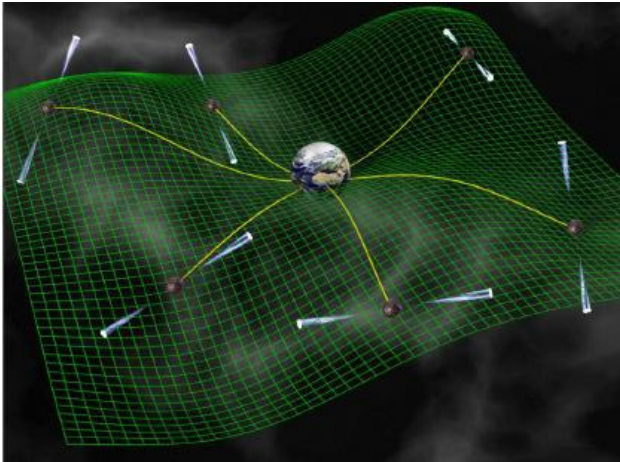
**GWs provide new opportunities
to explore HEP**

The early Universe is a HEP laboratory

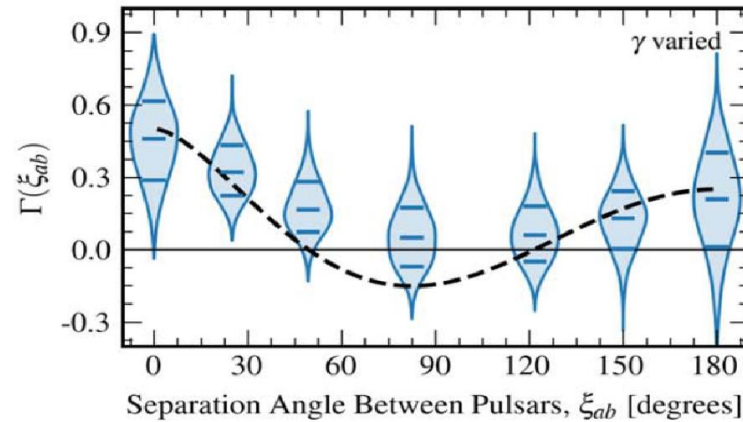


Evidence for the GWB

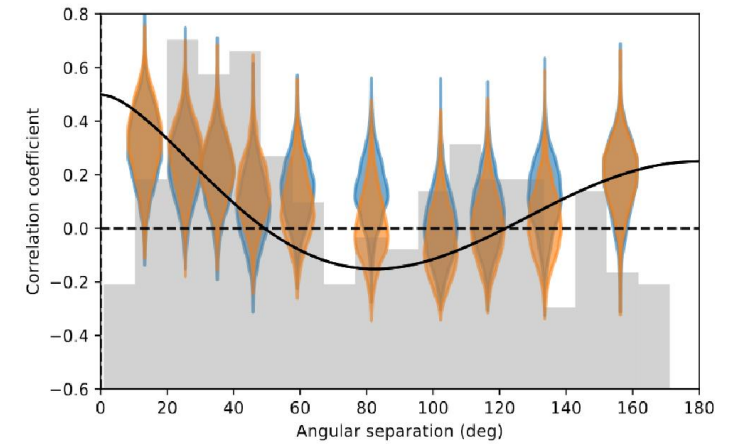
PTA experiments



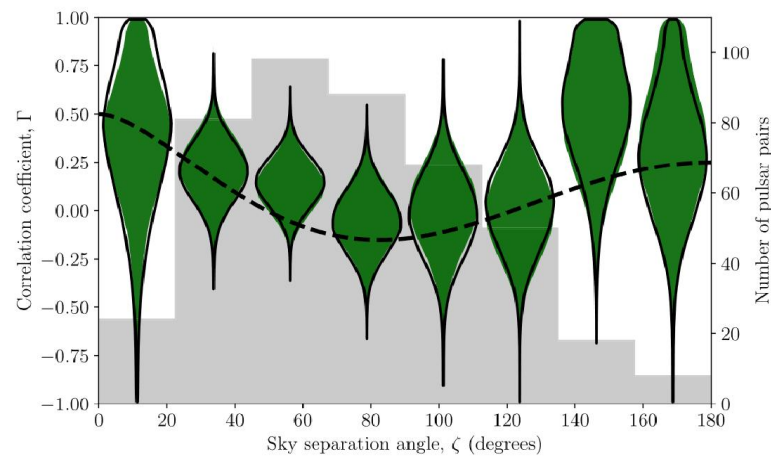
NANOGrav



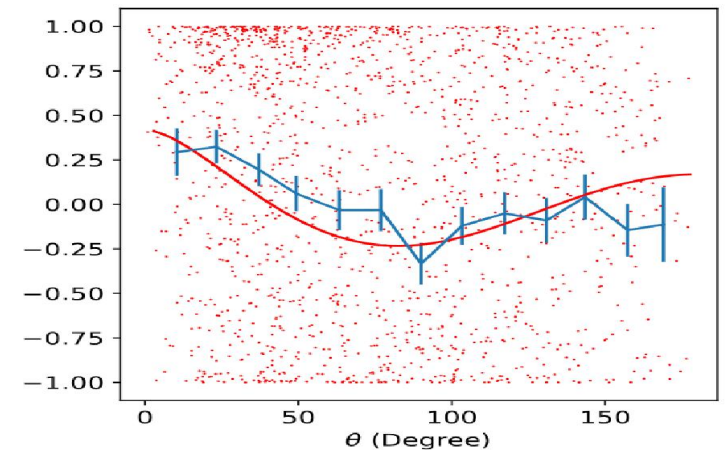
EPTA



PPTA



CPTA



ApJL 951 (2023) L8: NANOGrav

A&A 678 (2023) A50: EPTA, InPTA

ApJL 951 (2023) L6: PPTA

RAA 23 (2023) 075024: CPTA

GWB from the early Universe

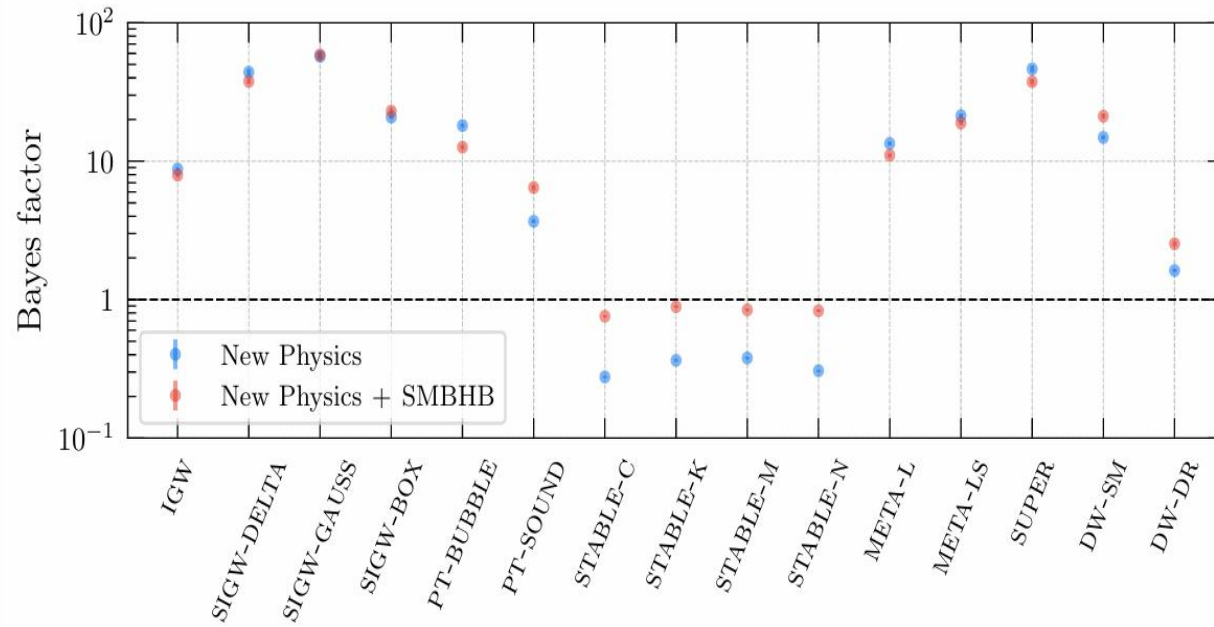


Figure 2. Bayes factors for the model comparisons between the new-physics interpretations of the signal considered in this work and the interpretation in terms of SMBHBs alone. Blue points are for the new physics alone, and red points are for the new physics in combination with the SMBHB signal. We also plot the error bars of all Bayes factors, which we obtain following the bootstrapping method outlined in Section 3.2. In most cases, however, these error bars are small and not visible.

✓ astrophysical origins

- SMBHB

✓ cosmological origins

- inflation
- preheating
- phase transition
- topological defect
- scalar perturbations
-

Induced GWs

induced GWs

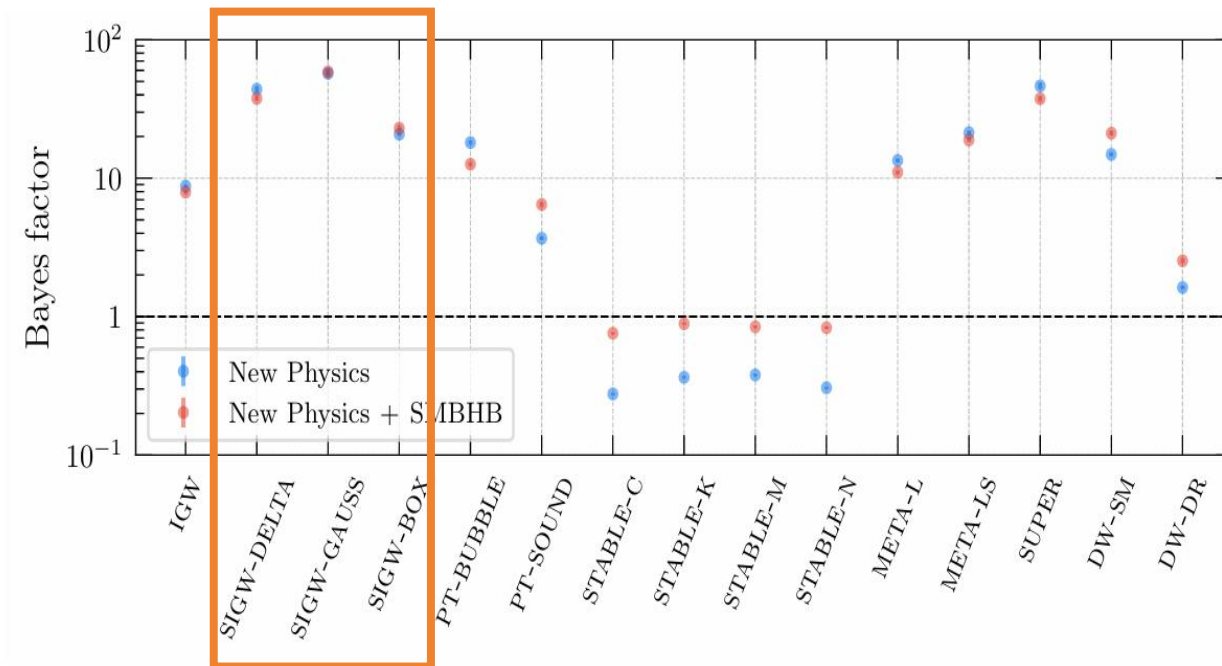


Figure 2. Bayes factors for the model comparisons between the new-physics interpretations of the signal considered in this work and the interpretation in terms of SMBHBs alone. Blue points are for the new physics alone, and red points are for the new physics in combination with the SMBHB signal. We also plot the error bars of all Bayes factors, which we obtain following the bootstrapping method outlined in Section 3.2. In most cases, however, these error bars are small and not visible.

✓ astrophysical origins

- SMBHB

✓ cosmological origins

- inflation
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-

Induced GWs

$$ds^2 = a^2 \left\{ -(1 + 2\phi^{(1)}) d\tau^2 + \left[(1 - 2\phi^{(1)})\delta_{ij} + \frac{1}{2}h_{ij}^{(2)} \right] dx^i dx^j \right\}$$



$$h_{\lambda,\mathbf{k}}^{(2)''} + 2\mathcal{H}h_{\lambda,\mathbf{k}}^{(2)'} + k^2 h_{\lambda,\mathbf{k}}^{(2)} = \mathcal{S}_{\lambda,\mathbf{k}}^{(2)} \sim \phi_{\mathbf{k}-\mathbf{q}}^{(1)} \phi_{\mathbf{q}}^{(1)}$$



$$\Omega_{\text{gw}}(k) = \frac{k^2}{6a^2 H^2} \int_0^\infty du \int_{|1-u|}^{|1+u|} dv \left[\frac{4v^2 - (1 + v^2 - u^2)^2}{4uv} \right]^2 \times \overline{I^2(u, v, k, \tau)} \mathcal{P}_\zeta(uk) \mathcal{P}_\zeta(vk)$$

$$\phi_{\mathbf{k}}^{(1)}(\eta) = (2/3) \Phi(k, \eta) \zeta_{\mathbf{k}}$$

transfer function

primordial
curvature
perturbations

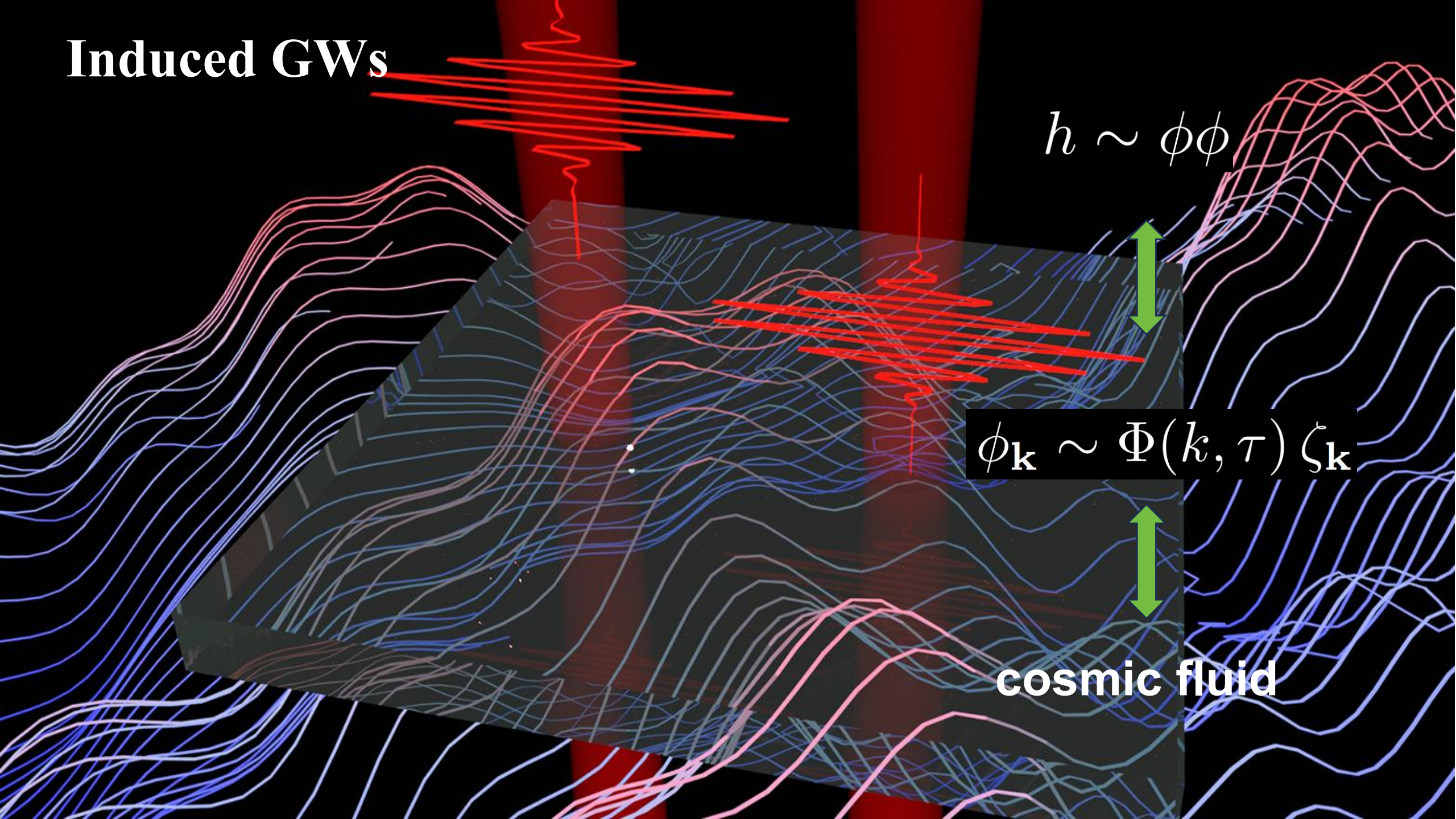
PRD 75 (2007) 123518: K.N. Ananda, C. Clarkson, D. Wands
 PRD 76 (2007) 084019: D. Baumann, P.J. Steinhardt, K. Takahashi, K. Ichiki
 JCAP 09 (2018) 012: J.R. Espinosa, D. Racco, A. Riotto
 PRD 97 (2018) 123532: K. Kohri, T. Terada

Induced GWs

$$h \sim \phi\phi$$

$$\phi_{\mathbf{k}} \sim \Phi(k, \tau) \zeta_{\mathbf{k}}$$

cosmic fluid

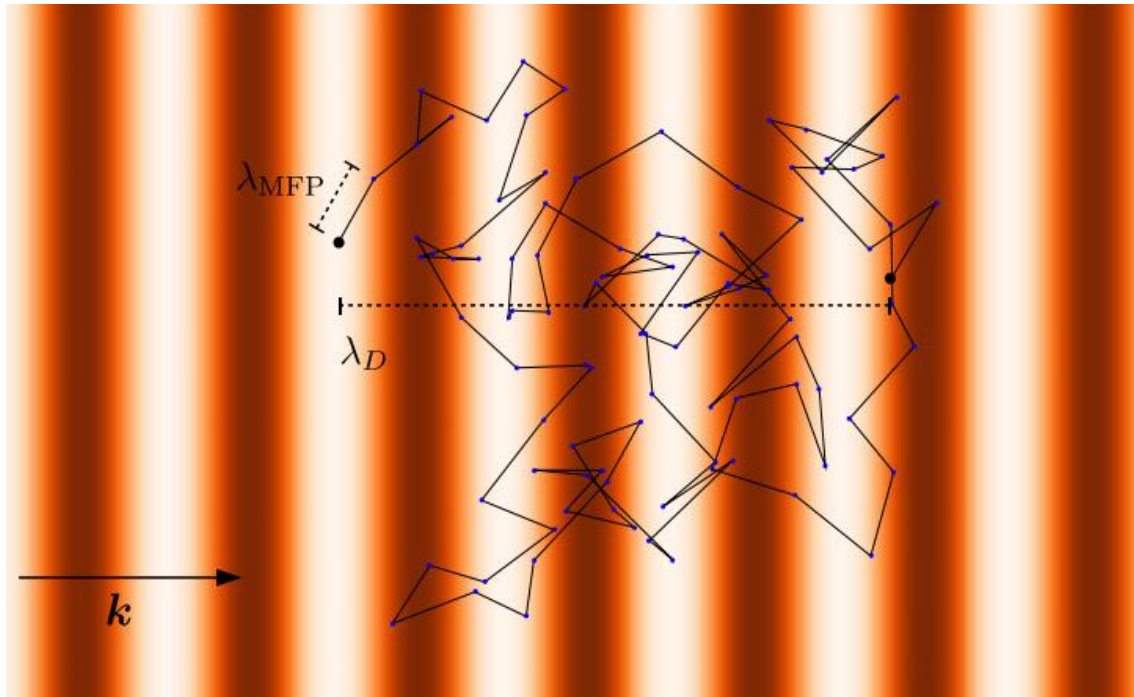


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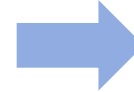
Cosmic fluid as an imperfect fluid

cosmic fluid



perturbation scale $k^{-1} \ll$ diffusion scale k_D^{-1}

Particle diffusion erases perturbations !



$$T_{\alpha\beta} = pg_{\alpha\beta} + (\rho + p) u_{\alpha}u_{\beta} + \Delta T_{\alpha\beta}(\eta, \xi, \chi)$$

shear viscosity

bulk viscosity

$$\Delta T_{ij} = \boxed{\eta} \left(\frac{\partial u_i}{\partial x^j} + \frac{\partial u_j}{\partial x^i} - \frac{2}{3} \delta_{ij} \nabla \cdot \mathbf{u} \right) - \boxed{\xi} \delta_{ij} \nabla \cdot \mathbf{u} ,$$

$$\Delta T_{0i} = \boxed{\chi} \left(\frac{\partial T}{\partial x^i} + T \frac{\partial u_i}{\partial t} \right) ,$$

$$\Delta T_{00} = 0$$

thermal conduction



Water

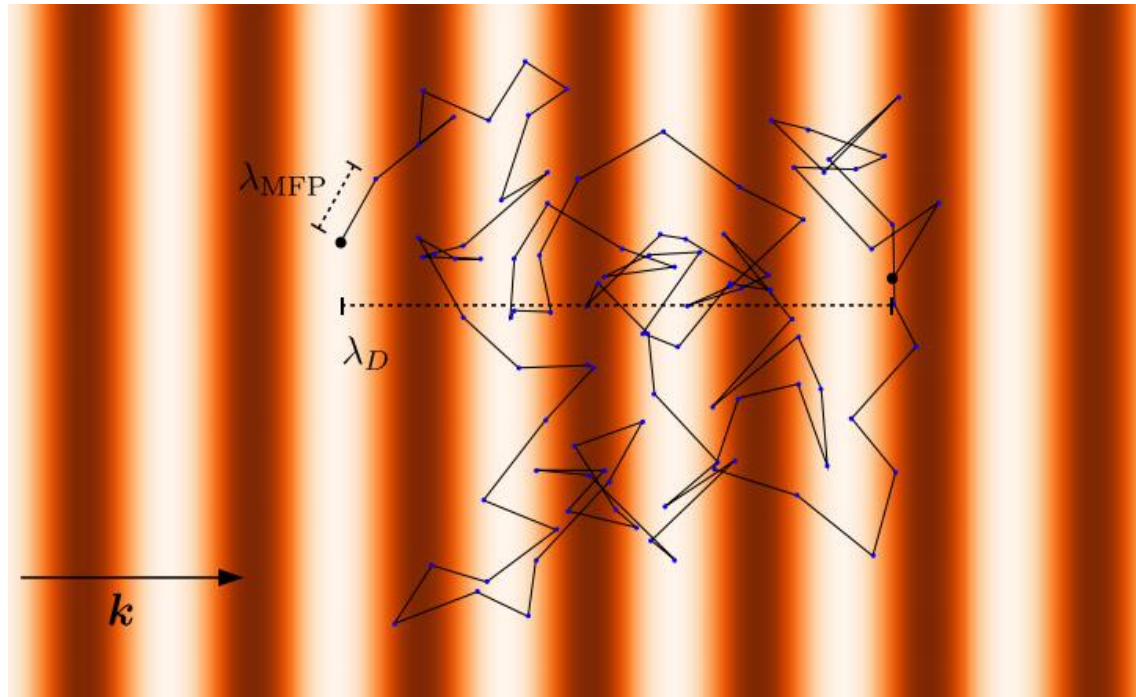


Syrup

ApJ 168 (1971) 175: S. Weinberg

Silk damping in the CMB

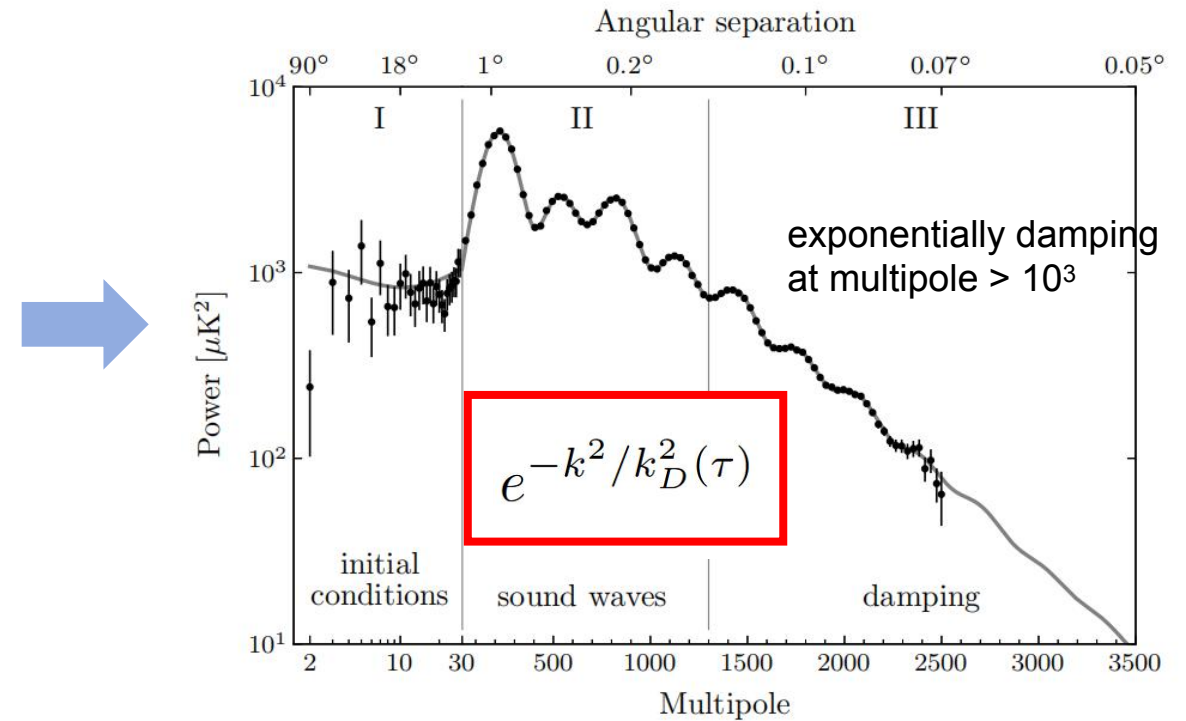
photon-baryon plasma



perturbation scale $k^{-1} \ll$ diffusion scale k_D^{-1}

Particle diffusion erases perturbations !

CMB power spectrum

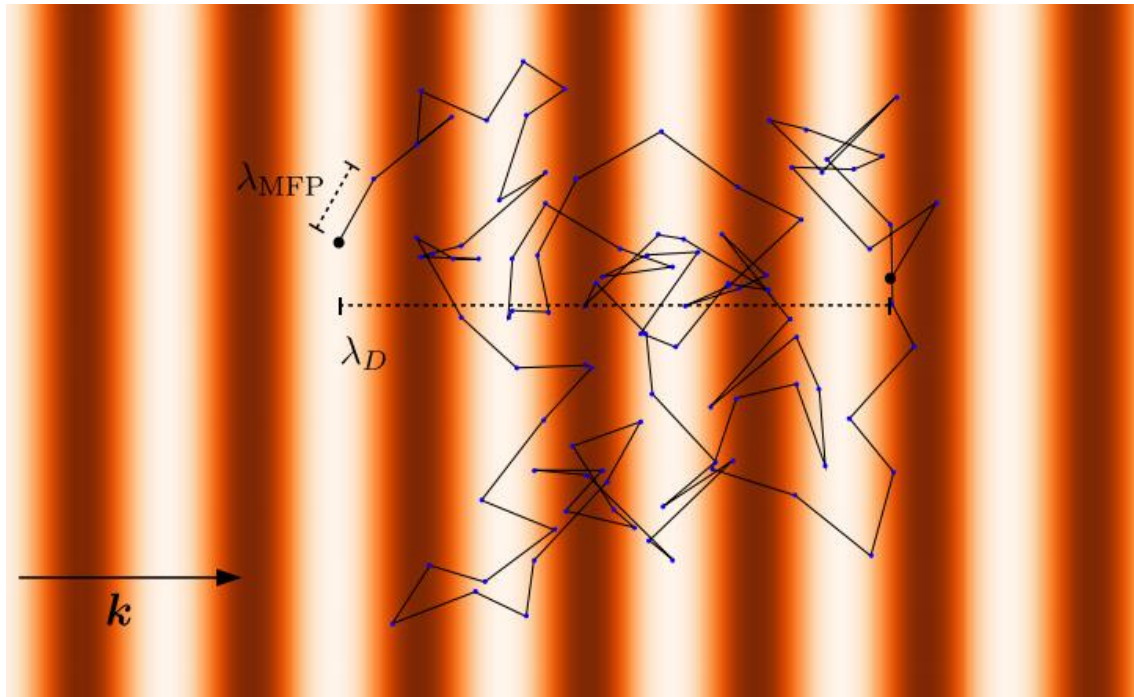


“Silk damping”

Nature 215 (1967) 5106: J. Silk

Silk damping in the GWB

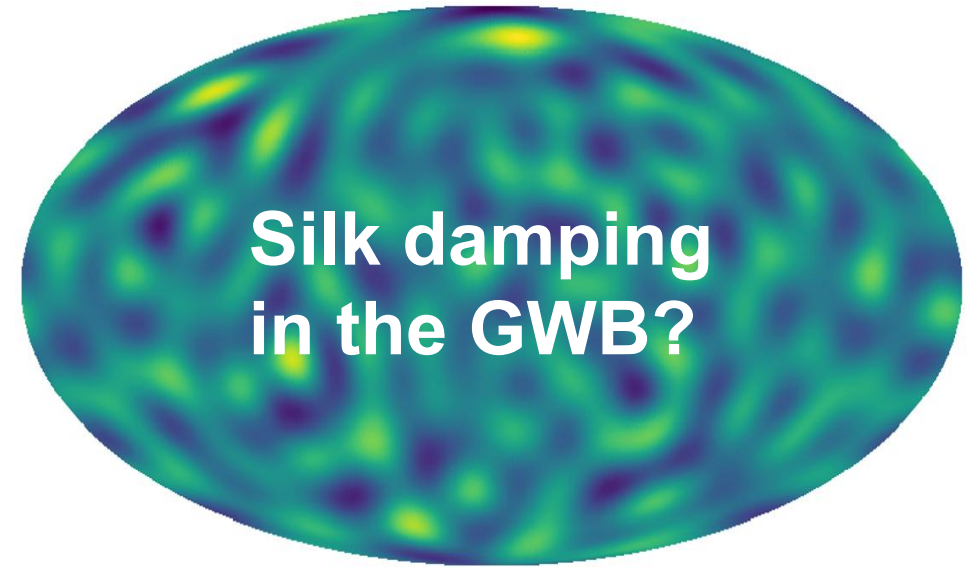
cosmic fluid



perturbation scale $k^{-1} \ll$ diffusion scale k_D^{-1}

Particle diffusion erases perturbations !

GWB

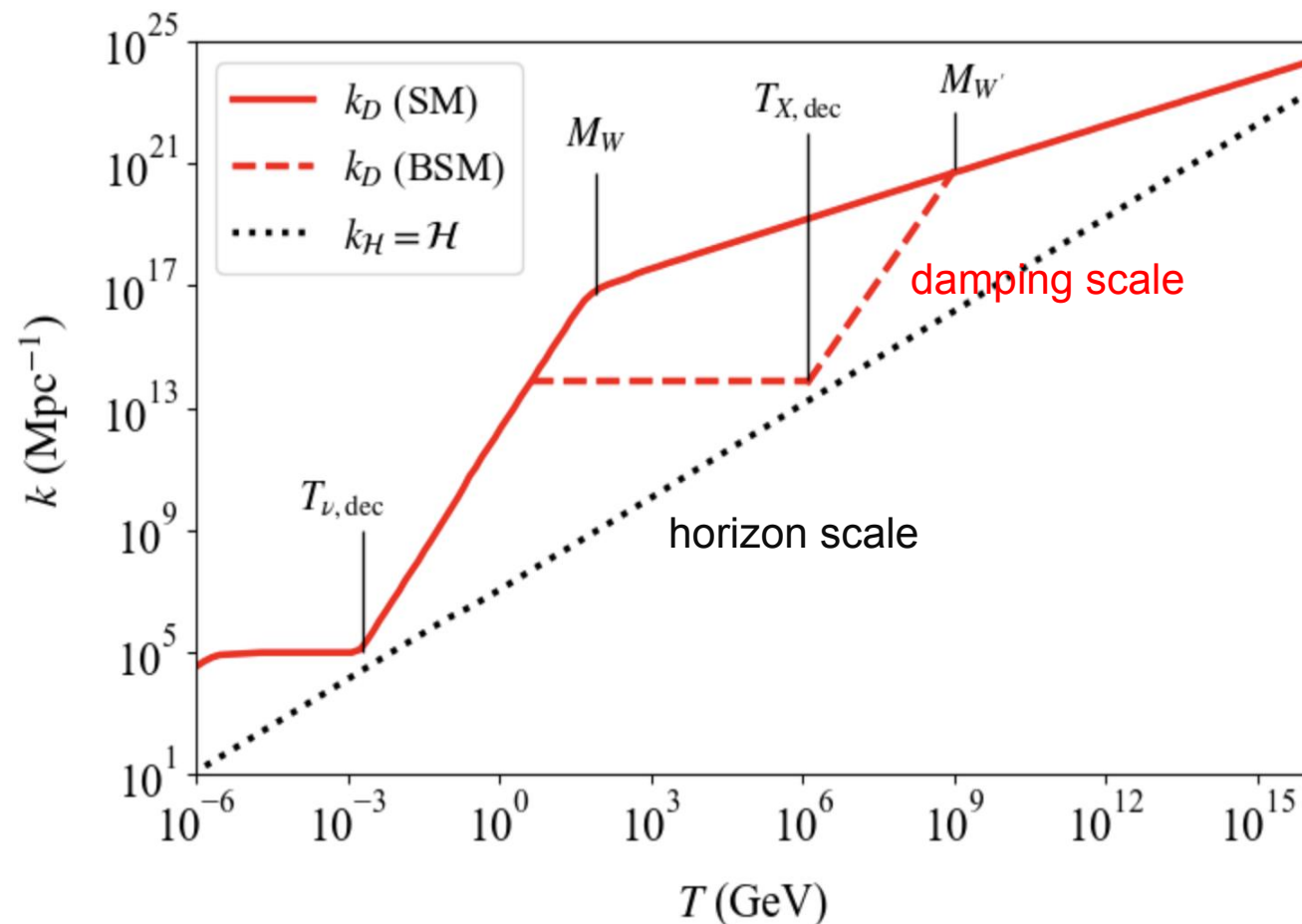


$$\Phi(k, \tau) \simeq \frac{9}{(k\tau)^2} \left(\frac{\sqrt{3}}{k\tau} \sin \frac{k\tau}{\sqrt{3}} - \cos \frac{k\tau}{\sqrt{3}} \right) \times e^{-k^2/k_D^2(\tau)}$$

perfect fluid, RD

Silk damping

Damping scale



➤ Determined by particle interactions

$$k_D^{-2}(\tau) \simeq \int_0^\tau d\tau' \frac{2\eta(\tau')}{3a(\rho+p)}$$

$$\eta(\tau) \simeq \sum_{j=\nu, X, \dots} \frac{4}{15} \rho_j t_j \Theta(\tau_{j, \text{dec}} - \tau)$$

$$t_j = 1/(n_j \langle \sigma_j v \rangle)$$

thermally-averaged
cross section

➤ Dominated by the weakest interaction

neutrinos &
new weakly-interacting particles

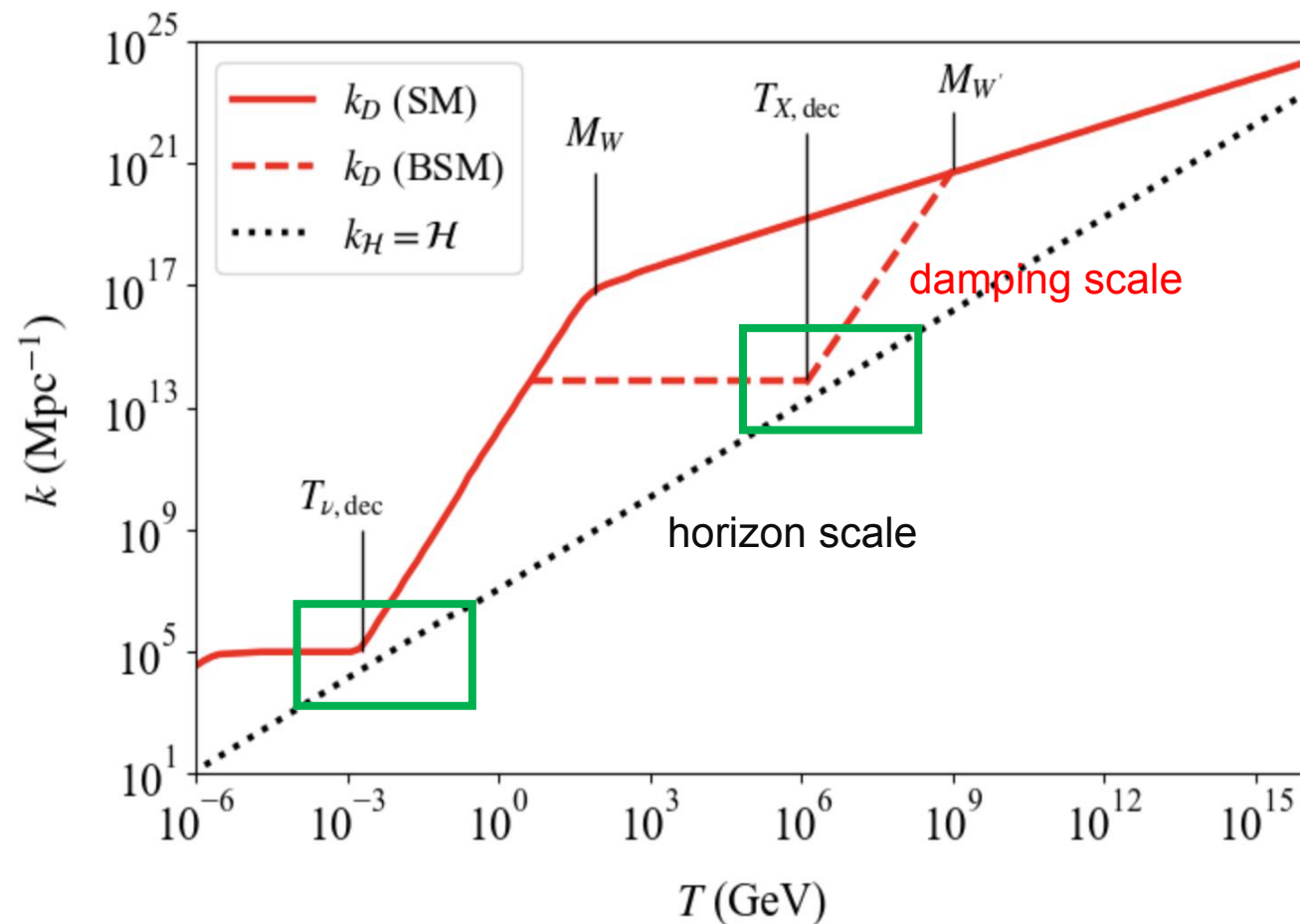
specific BSM models
can be considered

D. Jeong et al: PRL 113 (2014) 061301

YHY, S. Wang: SCPMA 68 (2025) 210412

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Damping scale



➤ At particle decoupling:

damping scale $\sim$ horizon scale

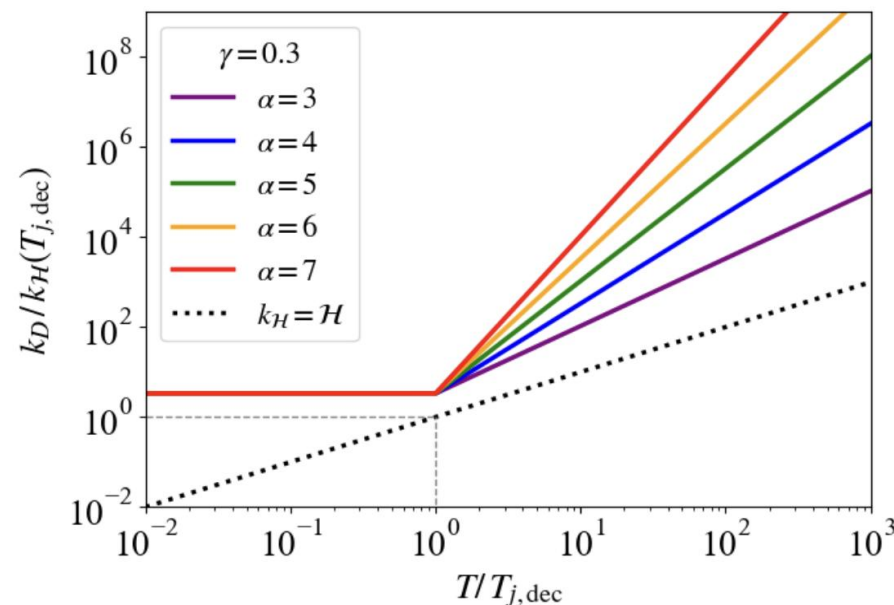
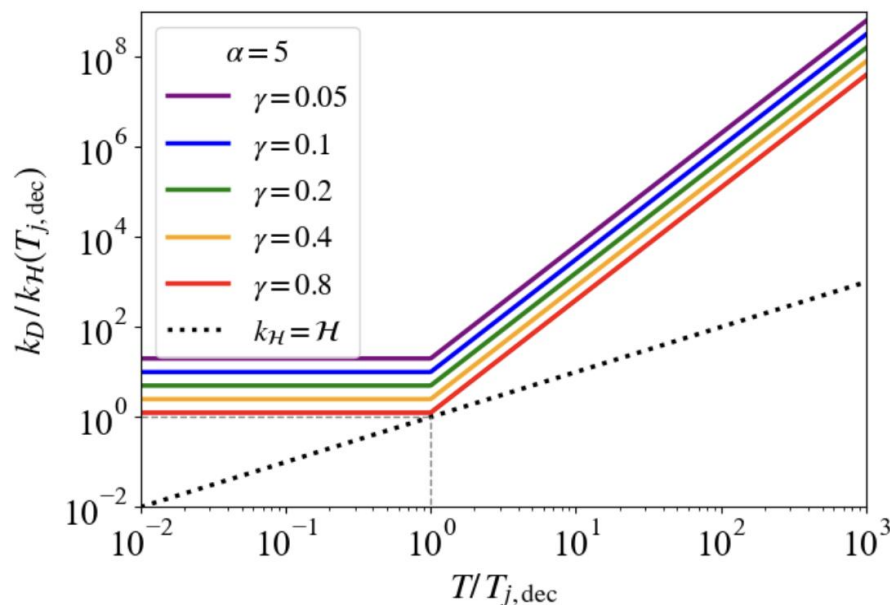
$$\frac{k_{D,j}}{k_{\mathcal{H},j}} \simeq \sqrt{\frac{15(m_j + 3)\rho}{2\rho_j}} \sim \mathcal{O}(1-10)$$

important for scalar-induced GWs!

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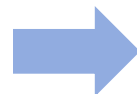
Parameter dependence



Silk damping scale

$$\frac{k_D(T)}{k_H(T_{j,\text{dec}})} \simeq \begin{cases} \gamma^{-1}, & T \lesssim T_{j,\text{dec}} \\ \gamma^{-1} \left(\frac{T}{T_{j,\text{dec}}} \right)^{\alpha/2}, & T \gtrsim T_{j,\text{dec}} \end{cases}$$

$$\langle \sigma_j v \rangle = \langle \sigma_j v \rangle_{\text{dec}} \left(\frac{T}{T_{j,\text{dec}}} \right)^{m_j}$$



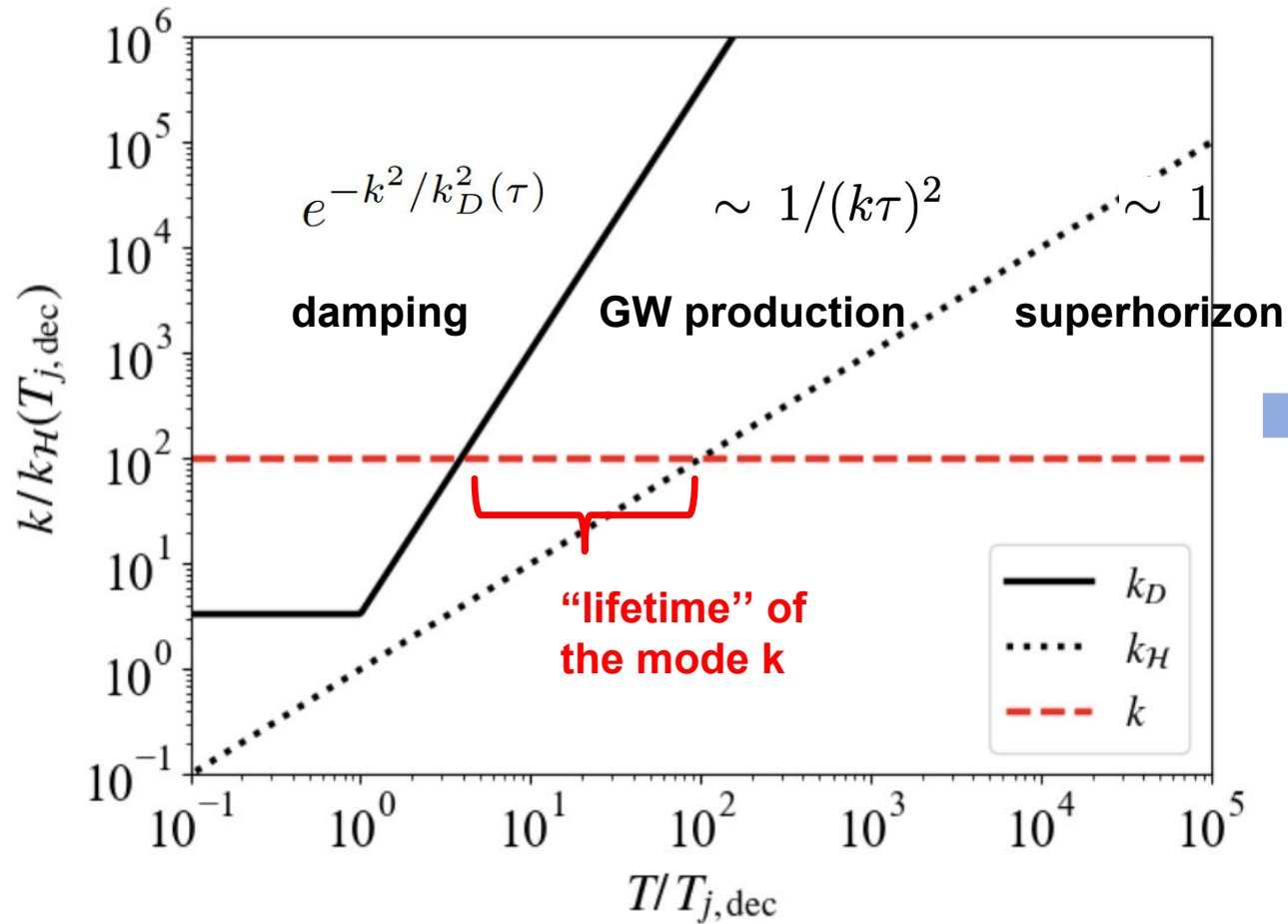
particle interaction & abundance

$$\alpha \simeq m_j + 3$$

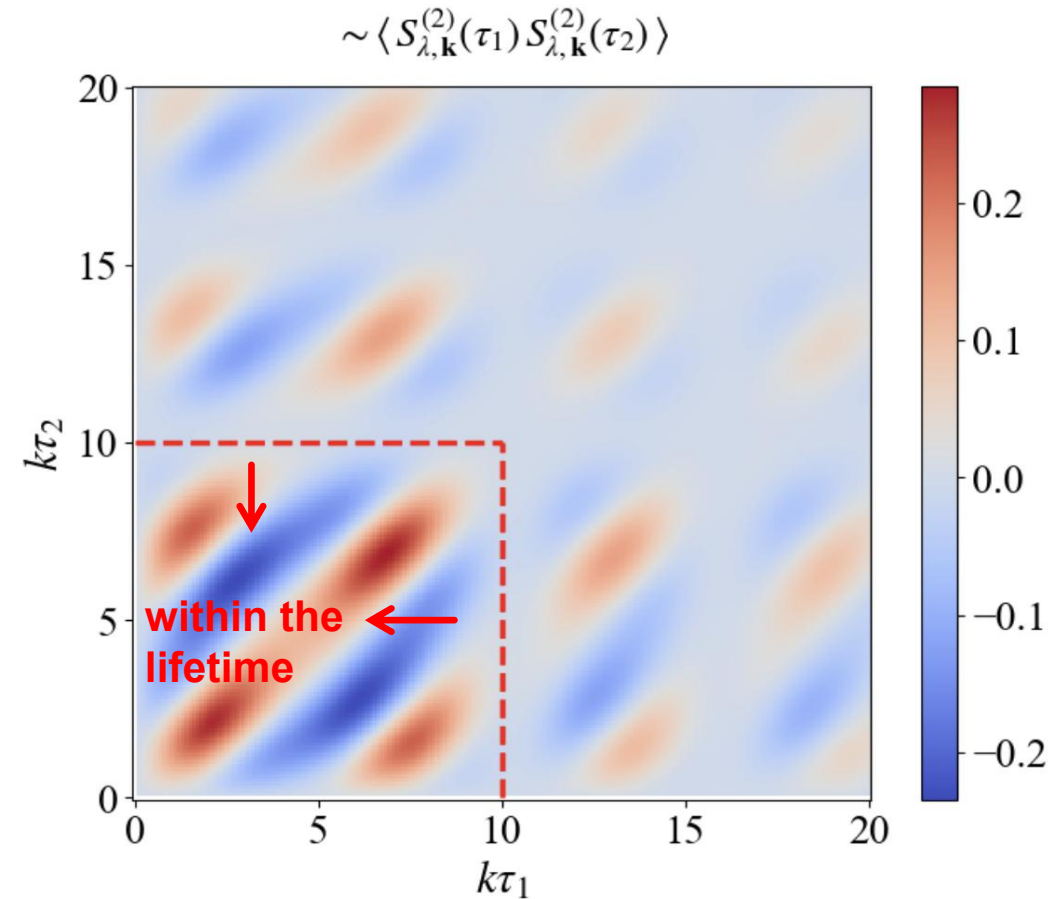
$$\gamma \simeq \sqrt{\frac{2\rho_j}{15(m_j + 3)\rho}}$$

Silk damping in induced GWs

evolution of scalar perturbations

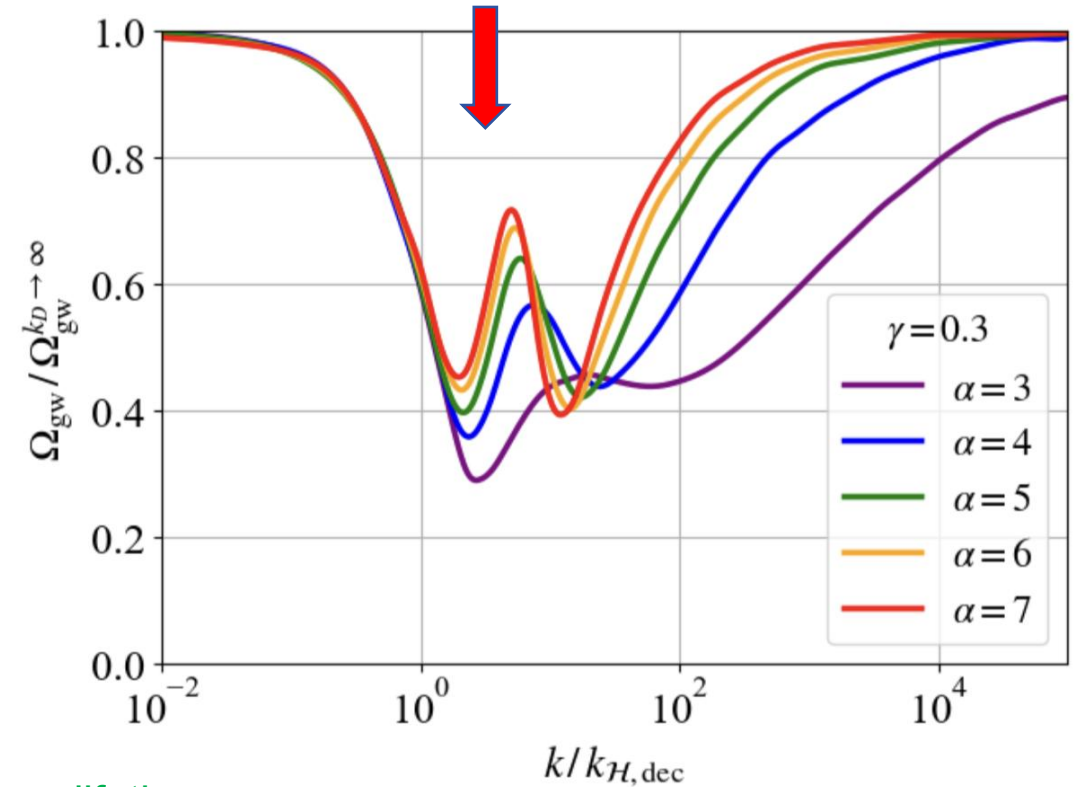
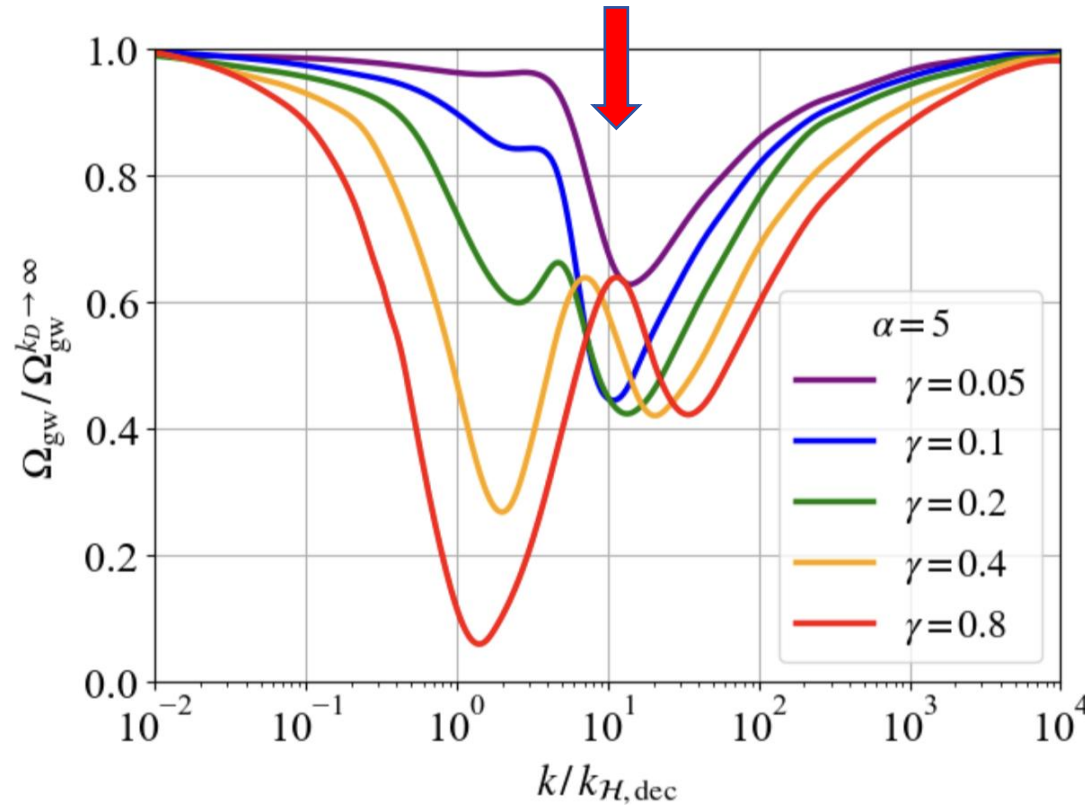


GW production



Silk damping in induced GWs

$$\mathcal{P}_\zeta(k) = \mathcal{A}_\zeta$$



positions of peaks/valleys:

$$k\tau_l(k, \alpha, \gamma) \sim \sqrt{3} n\pi, \quad n = 1, 2, \dots$$

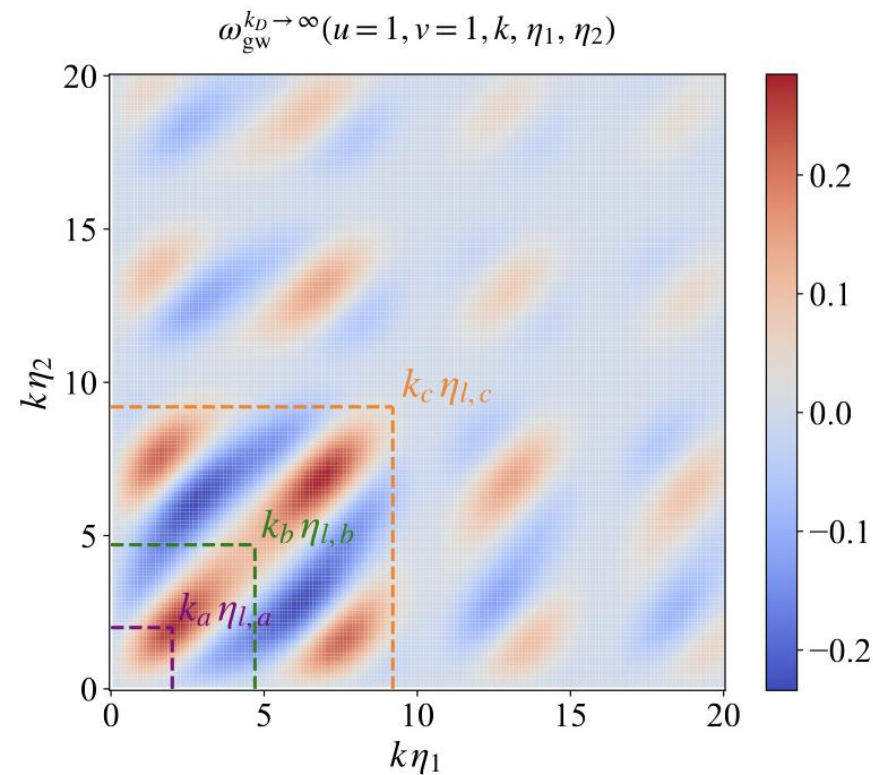
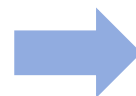
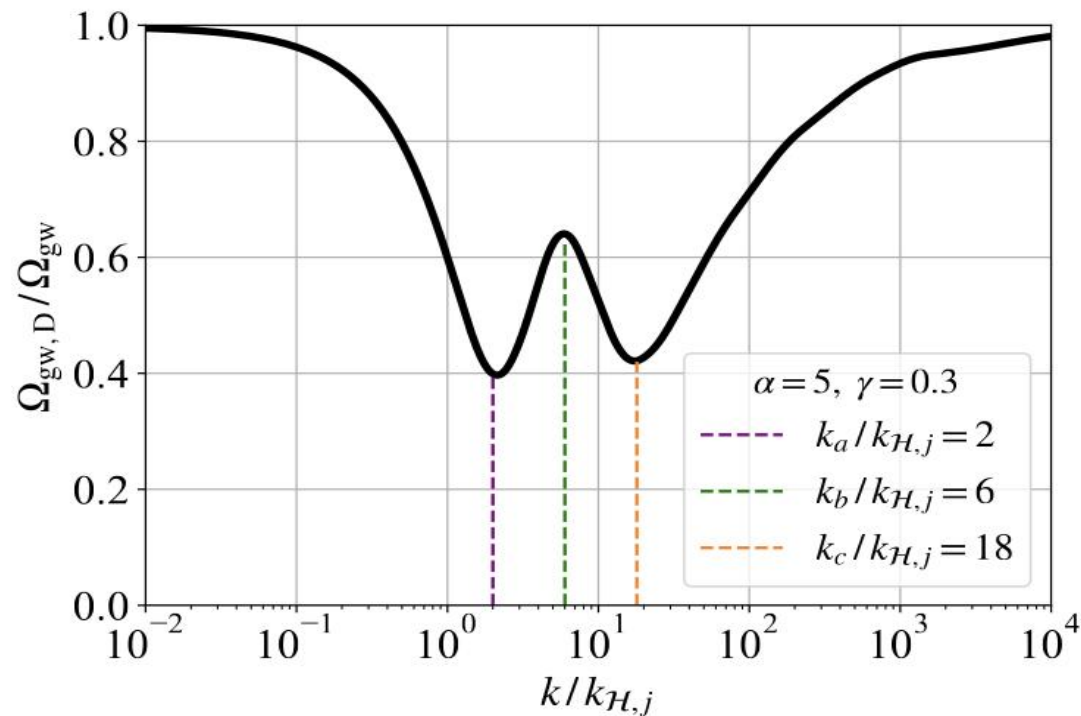
$$k/k_{\mathcal{H},\text{dec}} \sim (\sqrt{3} n\pi)^{\alpha/(\alpha-2)} \gamma^{2/(\alpha-2)}, \quad n = 1, 2, \dots$$

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Silk damping in induced GWs

$$\mathcal{P}_\zeta(k) = \mathcal{A}_\zeta$$



positions of peaks/valleys:

lifetime

$$k\tau_l(k, \alpha, \gamma) \sim \sqrt{3} n\pi, \quad n = 1, 2, \dots$$

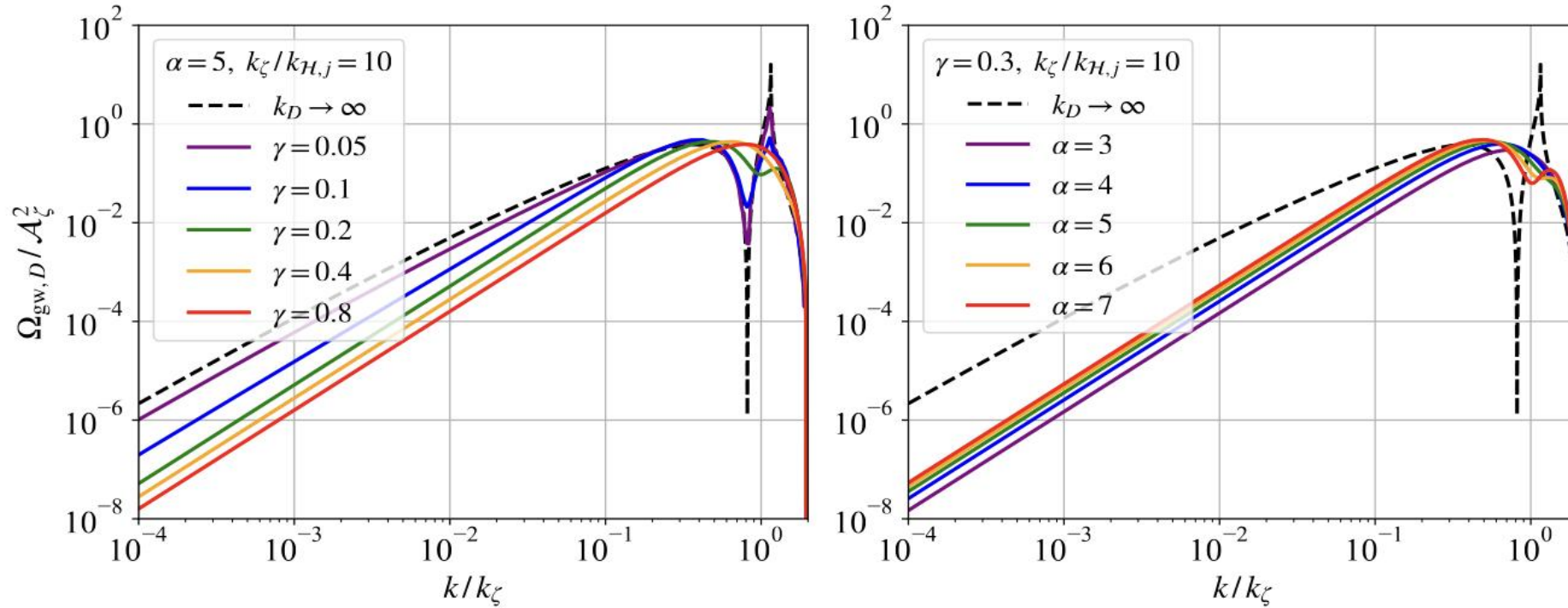
$$k/k_{\mathcal{H},\text{dec}} \sim (\sqrt{3} n\pi)^{\alpha/(\alpha-2)} \gamma^{2/(\alpha-2)}, \quad n = 1, 2, \dots$$

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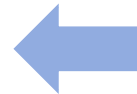
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Silk damping in induced GWs

$$\mathcal{P}_\zeta(k) = \mathcal{A}_\zeta \delta\left(\ln \frac{k}{k_\zeta}\right)$$



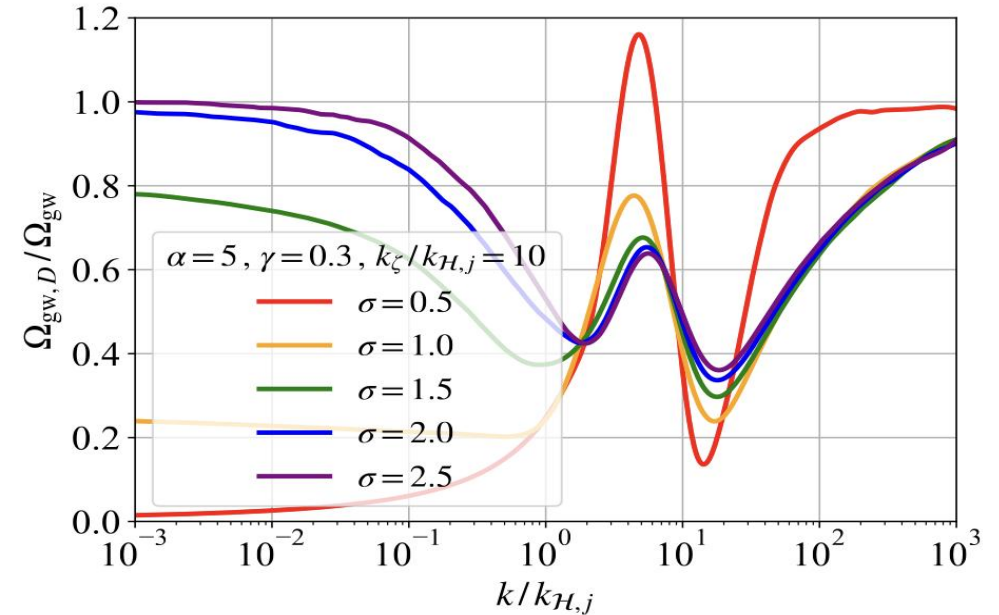
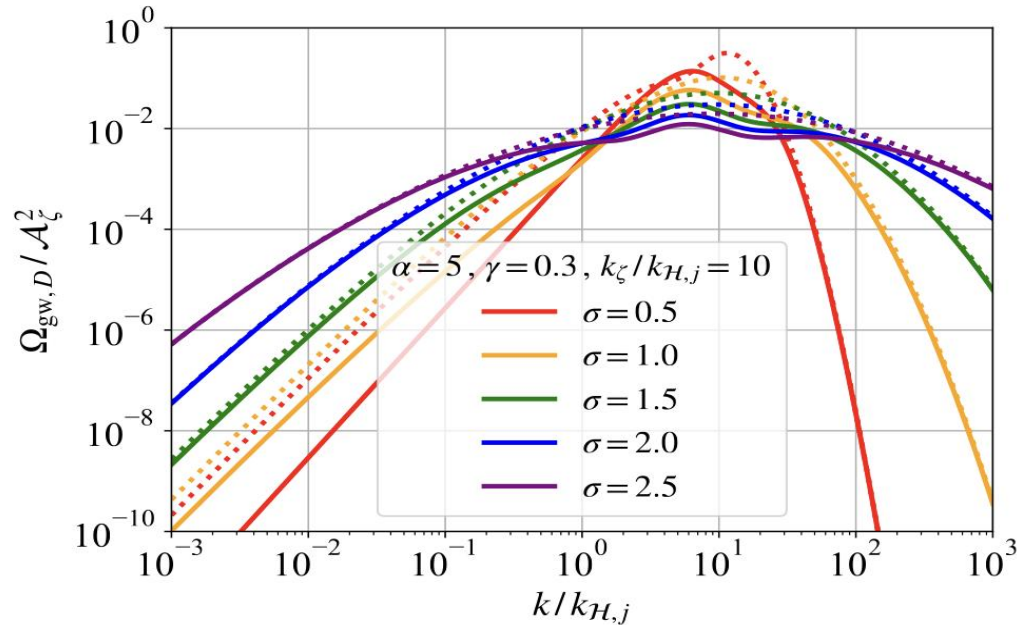
- infrared scaling: $k^2 \ln^2 k \rightarrow k^2$
- smoothing the resonant peak



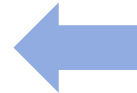
**finite damping-
induced lifetime**

Silk damping in induced GWs

$$\mathcal{P}_\zeta(k) = \frac{\mathcal{A}_\zeta}{\sqrt{2\pi\sigma}} e^{-\frac{1}{2\sigma^2} \ln^2(k/k_\zeta)}$$



- infrared scaling: $k^3 \ln^2 k \rightarrow k^3$
- double-valley structure



**finite damping-
induced lifetime**

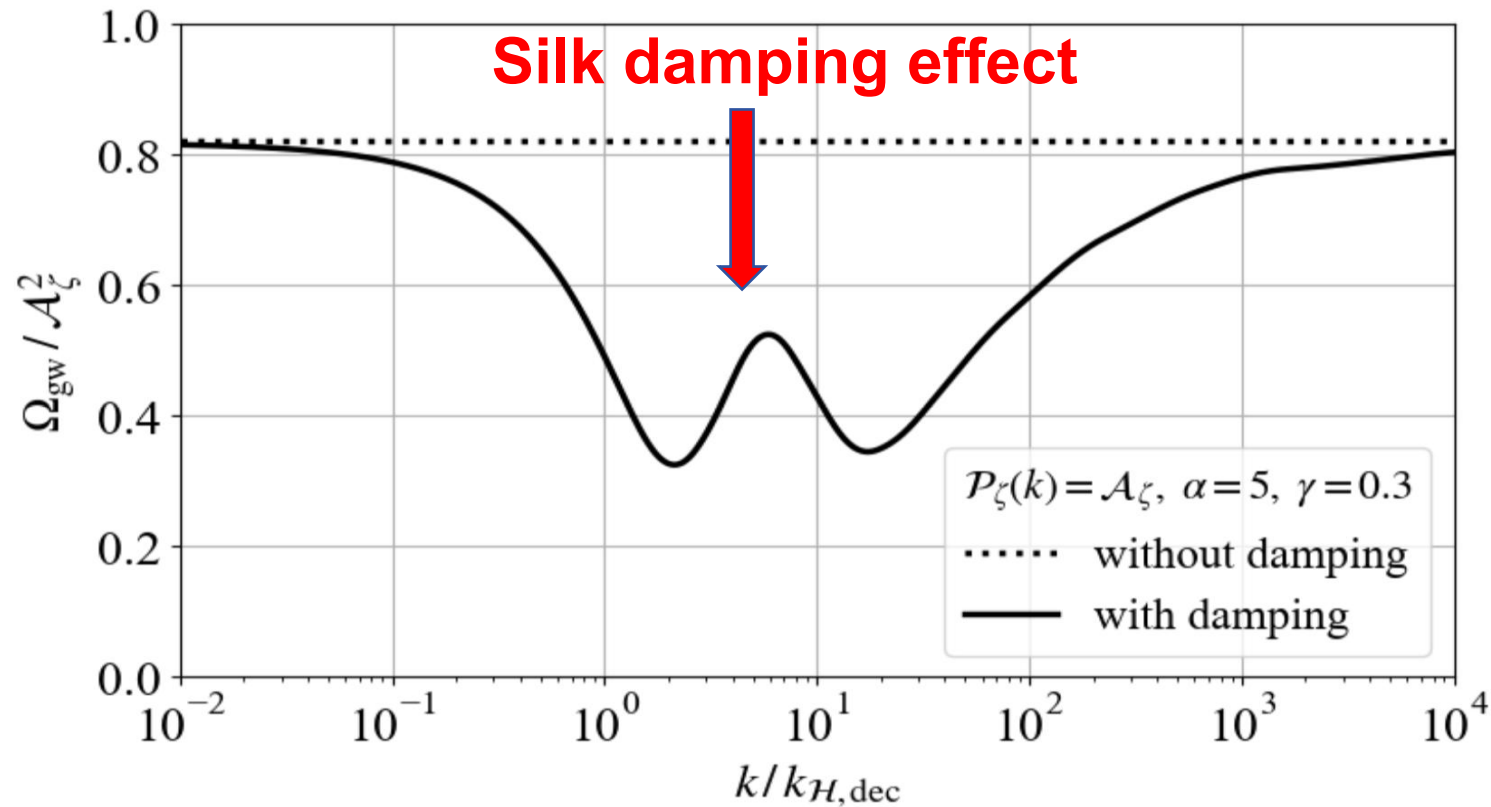
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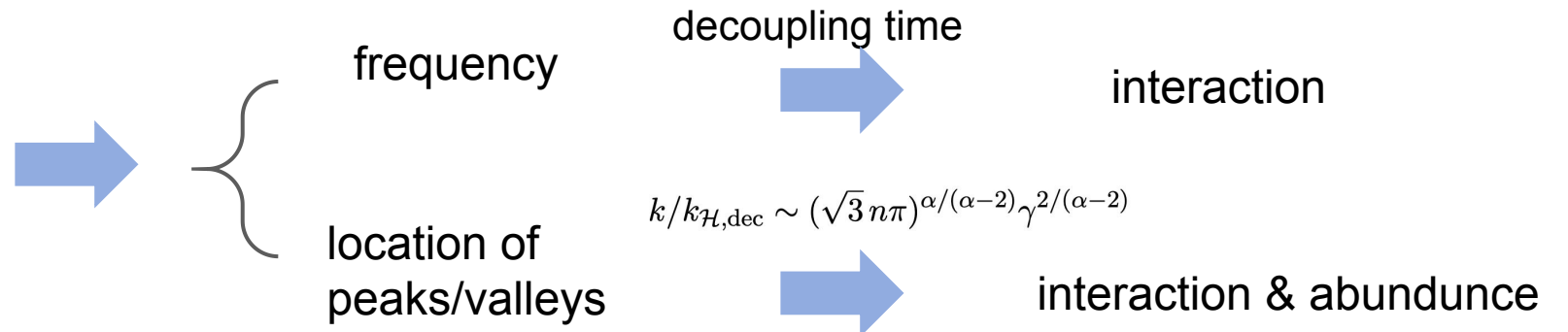
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Probing weakly-interacting particles

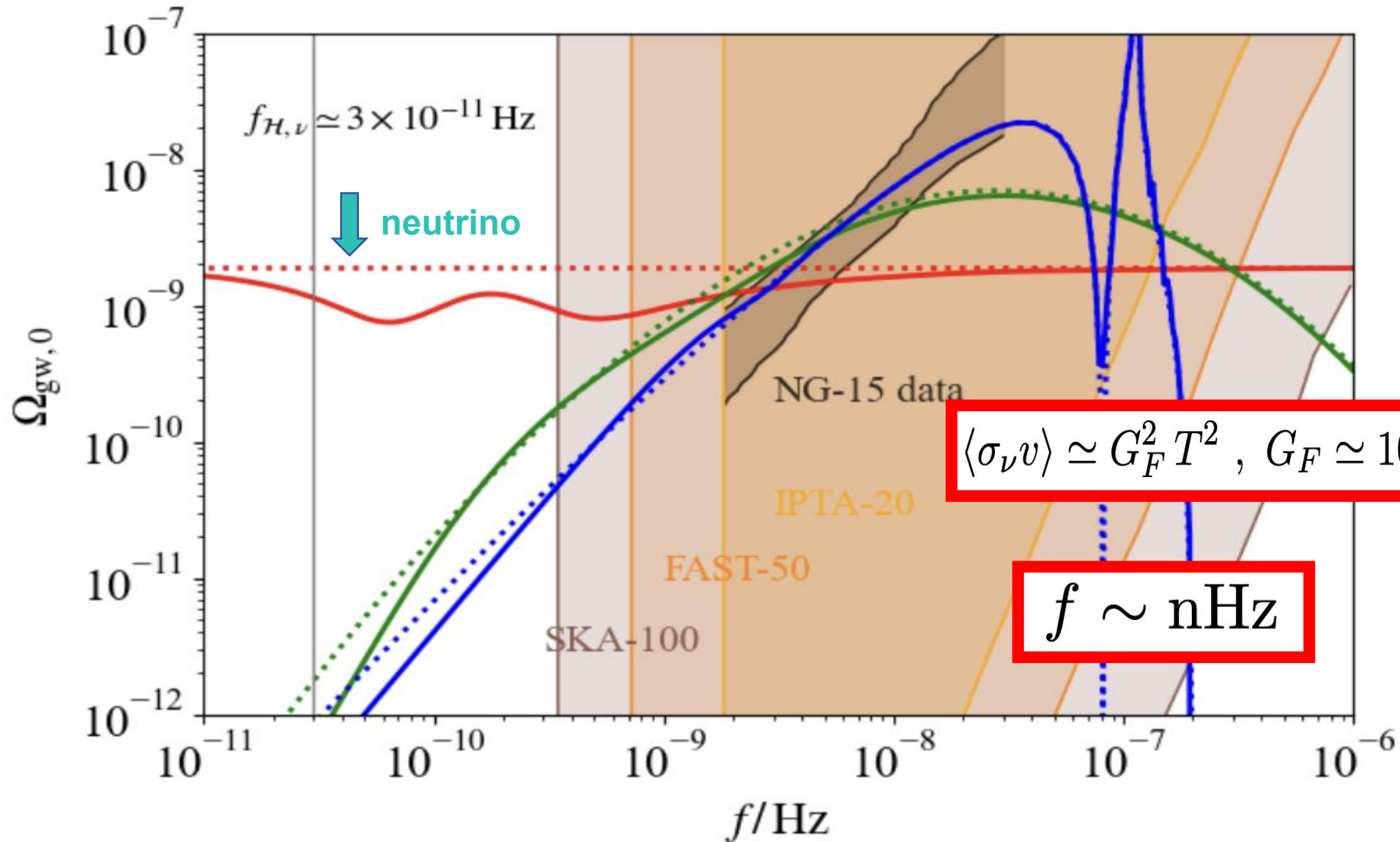


Silk damping can suppress
the GW spectrum by **~60%**
at the scale **$k \sim k_{\mathcal{H},\text{dec}}$**



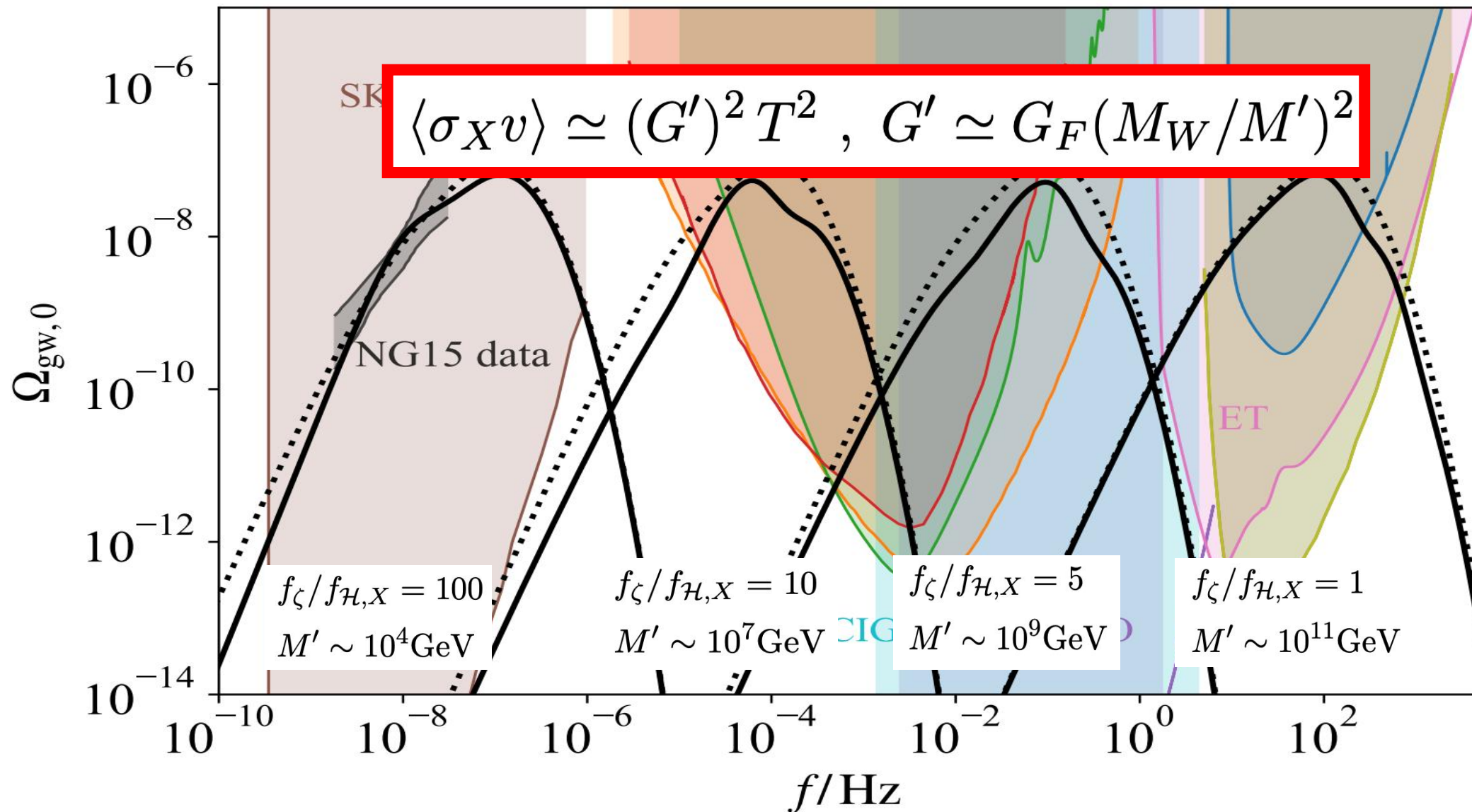
Observation (SM)

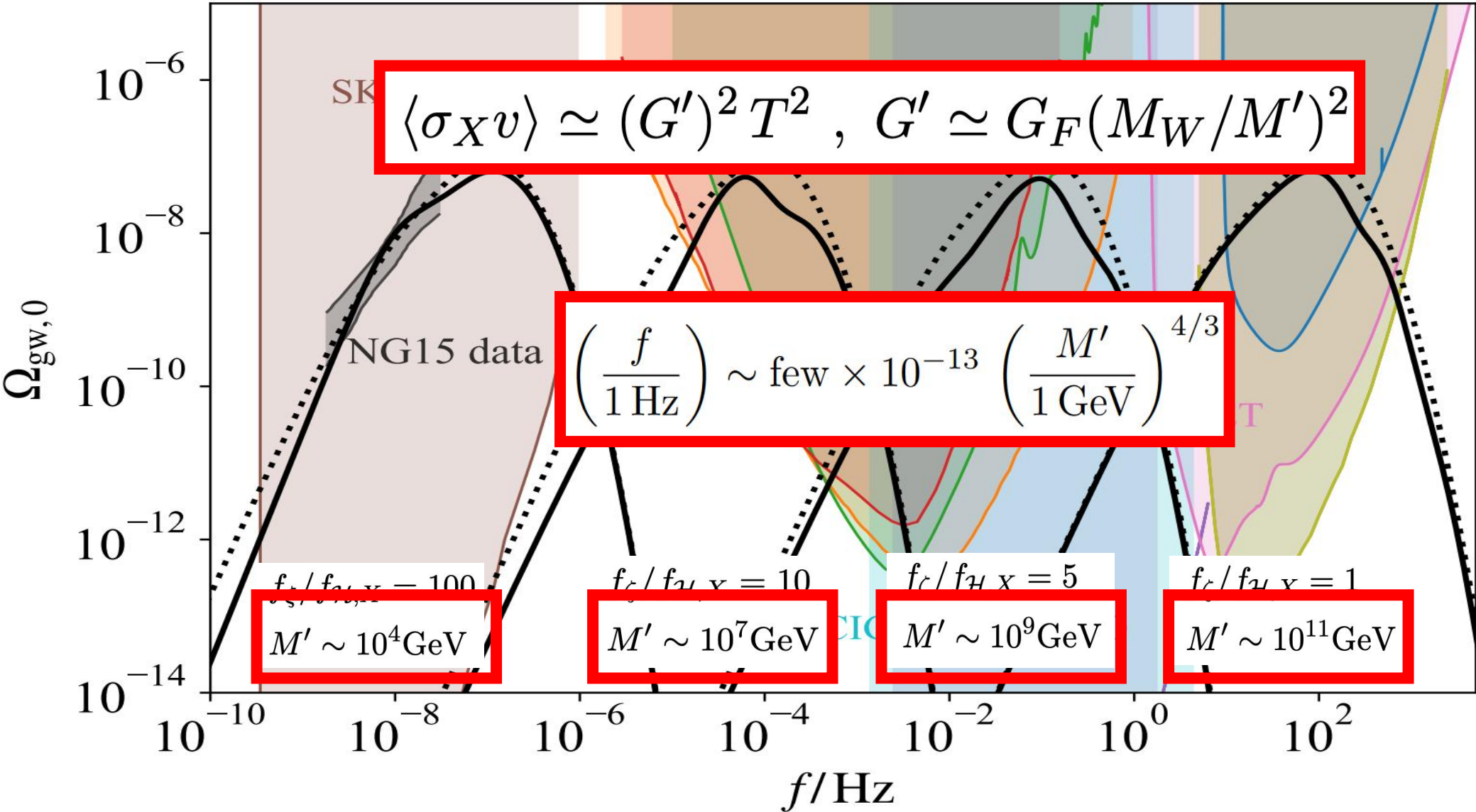
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Observation (BSM)

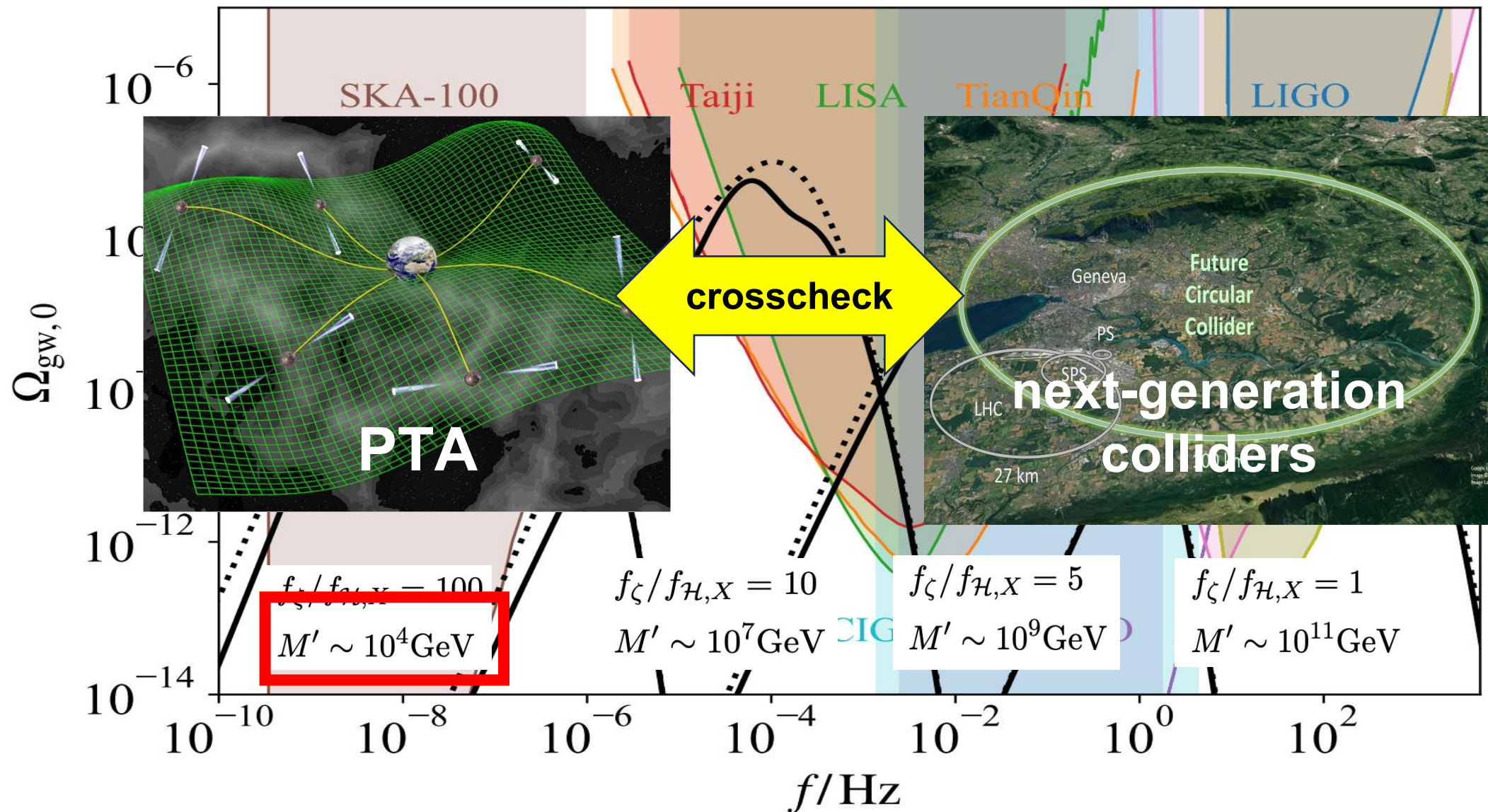
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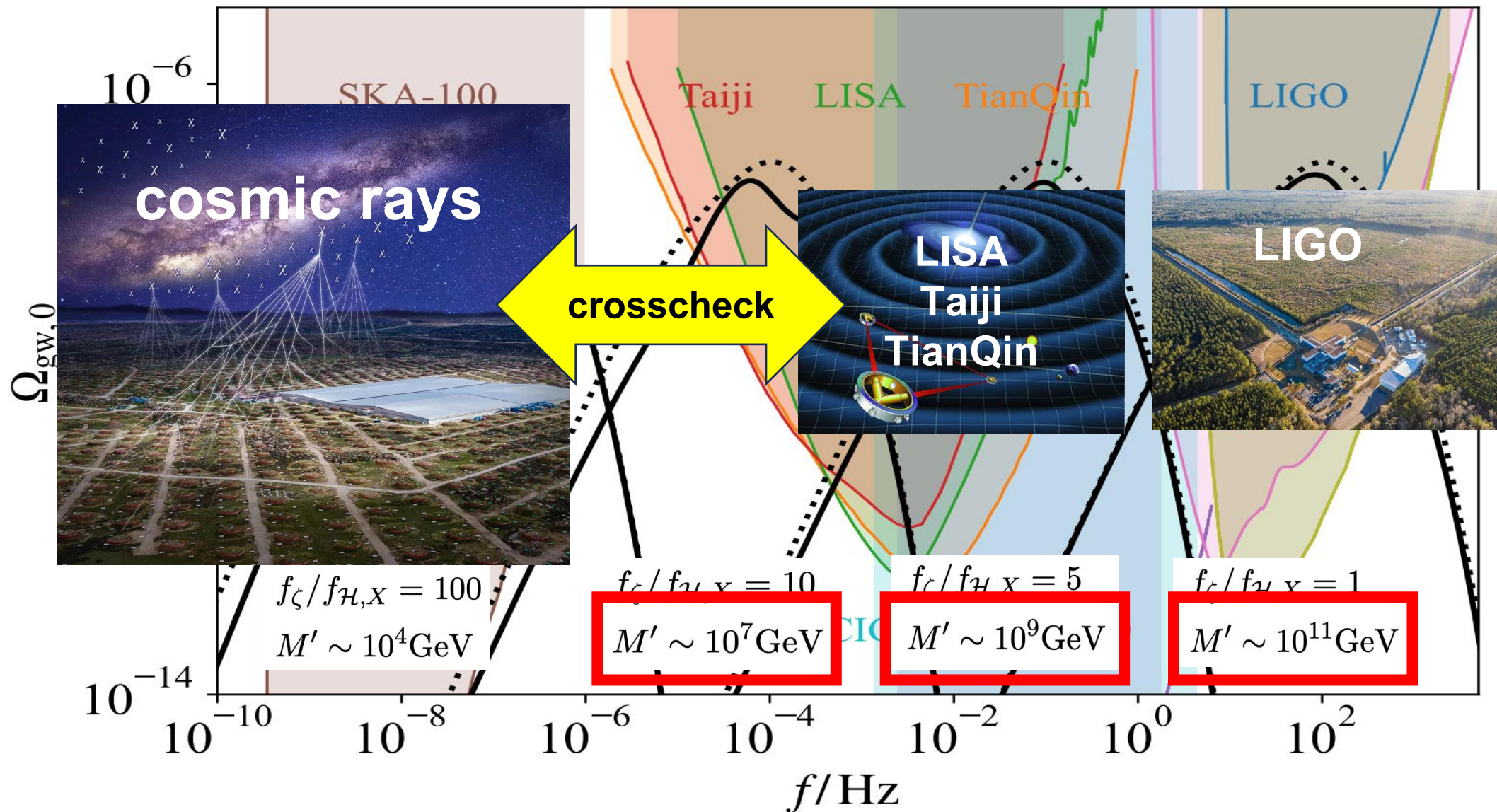
Future detection

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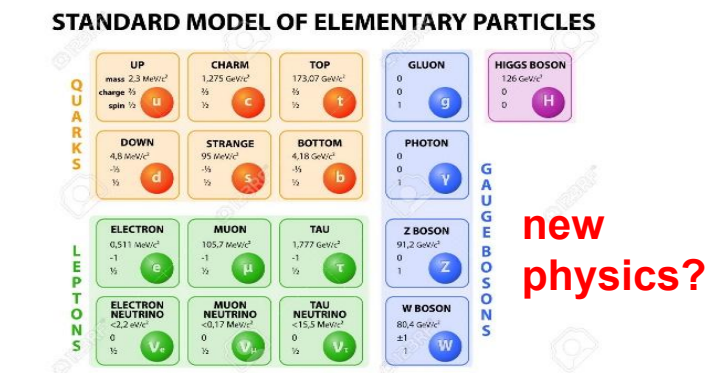
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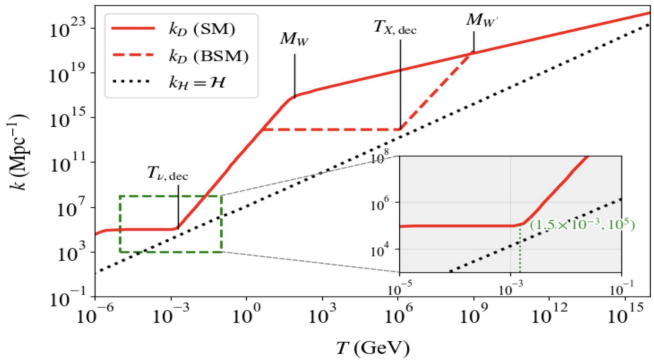


Summary

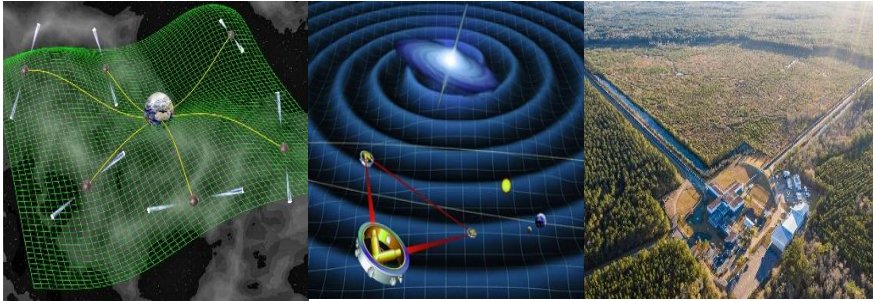
Particle interaction



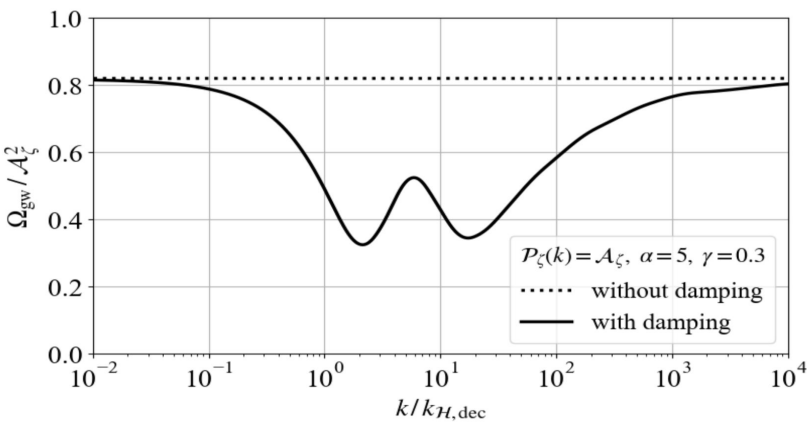
Silk damping



GW observation



induced GWs



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Summary

- Silk damping are essential yet unexplored in the study of induced GWs.
- Silk damping leads to characteristic suppression on the GW spectrum at the frequencies related to the decoupling of weakly-interacting particles.
- Within the SM, Silk damping caused by neutrinos is important for PTA analysis.
- Beyond the SM, Silk damping in induced GWs provides a new framework to detect new physics, especially for those at extremely high energy scales.

Thanks!